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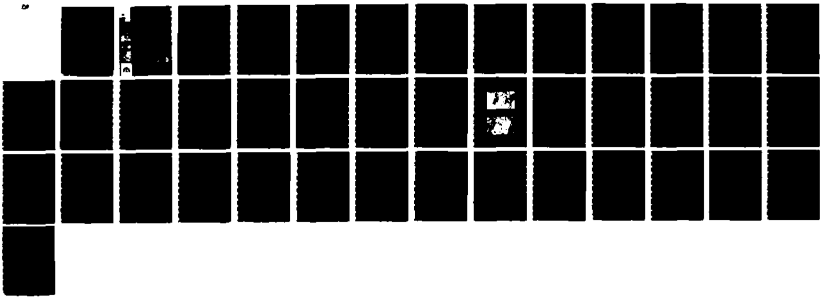

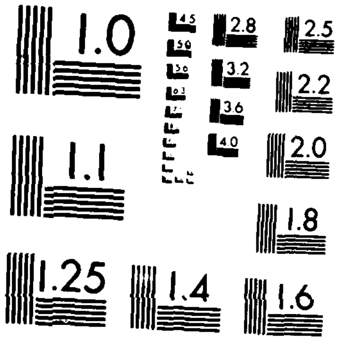

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EVALUATION OF THE FROST RESISTANCE OF ROLLER-COMPACTED CONCRETE PAVEMENTS

by

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US ARMY ENGINEER WATERWAYS EXPERIMENT STATION

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An investigation was conducted to evaluate the frost resistance of samples taken from roller-compacted concrete (RCC) pavements using laboratory testing procedures. Nine existing pavements were sampled and tested for microscopical determination of air-void content and parameters of the air-void system, resistance to rapid freezing and thawing, critical dilation, and compressive and flexural strength. The pavements ranged in age from 1 month to 8 years at the time of sampling.

Results of the rapid freezing-and-thawing tests indicate that the frost resistance of the concrete is, as might be expected, a function of the bubble spacing factor ($\bar{L}$) of the air-void system. Those samples having $\bar{L}$'s smaller than 0.011 in. generally had durability factors (DFE_{300}) of 60 or greater. Those samples having $\bar{L}$'s greater than 0.016 in. generally had DFE_{300}'s less than 40. The samples having $\bar{L}$'s less than 0.016 in. also contained approximately 2.0 to 4.0 percent, by volume, of air voids, the sections of (Continued)

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which that were counted gave chord lengths that were less than 0.04 in. in length, but irregularly shaped. The presence of larger than anticipated amounts of small air voids appears to be related to cohesiveness of the mixture, pugmill mixing, and the method of compaction.

Preliminary results of the dilation tests indicate that those samples judged to be frost susceptible when tested by rapid freezing and thawing, may, in fact, offer some degree of frost resistance. The dilation test may be appropriate, therefore, to determine whether a RCC sample is frost resistant at the time of test or to measure the period of frost immunity.

PREFACE

This paper was prepared for presentation at the 65th Annual Meeting of the Transportation Research Board, Washington, D.C. The paper was presented on 14 January 1986 at Session 90, "Design, Construction, and Performance of Roller-Compacted Concrete Pavements." The investigation on which the paper was based was sponsored by the Office, Chief of Engineers (OCE), US Army, as part of the Facilities Investigation and Studies Program Work Unit 015, "Roller-Compacted Concrete Pavement Criteria Development." The Technical Monitor for the investigation was Mr. Sam Gillespie, DAEN-ECE-G. Funds for publication of this paper were provided from those made available for operation of the Concrete Technology Information Analysis Center (CTIAC). This is CTIAC Report No. 77.

The investigation was conducted during the period January 1985 - July 1985 at the US Army Engineer Waterways Experiment Station (WES), Structures Laboratory (SL). The work was conducted under the general supervision of Dr. William F. Marcuson, Chief, Geotechnical Laboratory (GL), and Messrs. Bryant Mather, Chief, SL, and John M. Scanlon, Chief, Concrete Technology Division (CTD), SL; and under the direct supervision of Mr. Kenneth L. Saucier, Chief, Concrete and Evaluation Group, CTD. Testing of concrete specimens at the US Army Corps of Engineers' North Pacific Division Laboratory was under the direction of Mr. James A. Paxton, and testing of concrete specimens at the US Army Corps of Engineers' Southwestern Division Laboratory was under the direction of Mr. Arthur Feese. Concrete specimen testing at WES was conducted by Messrs. Dale Glass, Dan Wilson, and Mike Lloyd, CTD. This paper was prepared by Mr. Steven A. Ragan, CTD.

COL Allen F. Grum, USA, was the previous Director of WES. COL Dwayne G. Lee, CE, is the present Commander and Director. Dr. Robert W. Whalin is Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
feet	0.3048	metres
inches	25.4	millimetres
ounces (US fluid)	29.57353	cubic centimetres
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic yard	0.59327642	kilograms per cubic metre
pounds (force) per square inch	0.00689476	megapascals
square yards	0.7645549	square metres

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

EVALUATION OF THE FROST RESISTANCE OF ROLLER-COMPACTED CONCRETE PAVEMENTS

PART I: INTRODUCTION

Background

1. The Commander, US Army Corps of Engineers, has recommended that all field operating activities having military construction and civil works design responsibilities consider the use of roller-compacted concrete (RCC) for various horizontal concrete construction applications (Department of the Army, 1985). These applications include tactical equipment shop paving, tracked vehicle wash facilities pavements, tank trails, open storage areas, and marshalling areas. Significant cost savings are anticipated when RCC is used in lieu of conventional concrete, due to the labor savings associated with the production, placement, and compaction of RCC. However, the frost resistance of RCC pavements is of concern, particularly since results from earlier investigations indicate difficulty in securing entrained air in RCC (Department of the Army, 1985a).

Purpose

2. The Waterways Experiment Station (WES) is currently conducting an extensive research program on RCC pavement criteria development. Included in this program is an investigation on RCC pavement frost resistance. The initial phase of this investigation, discussed in this paper, consisted of obtaining representative samples from existing RCC pavements, and performing

laboratory testing on them to determine the air-void system parameters and resistance to frost damage. A second phase is planned in order to determine whether materials and construction criteria can be developed which will produce relatively frost-resistant RCC pavements.

Scope

3. Nine RCC pavements were sampled and tested for microscopical determination of air-void content and parameters of the air-void system, resistance to rapid freezing and thawing, critical dilation, and compressive and flexural strength. While the majority of testing was conducted at WES, some of the rapid freezing and thawing and strength testing was performed by the US Army Corps of Engineers' North Pacific Division Laboratory (NPDL), Troutdale, OR, and Southwestern Division Laboratory (SWDL), Dallas, TX. A number of no-slump concrete beams were also fabricated by WES and NPDL during mixture proportioning studies and tested for resistance to rapid freezing and thawing and microscopical determination of air-void content and parameters of the air-void system.

PART II: RCC PAVEMENT DESCRIPTIONS

Ft. Stewart, GA

4. A 234-ft*-long by 20-ft-wide test section was constructed in July 1983. The pavement ranges in thickness from 9 to 13 in., and currently serves as an access from a tracked vehicle parking area to a series of tank trails.

5. The materials used in the RCC were batched in a weigh-batch type concrete plant and mixed in revolving-drum truck mixers. The mixture contained crushed coarse aggregate conforming to ASTM C 33 (American Society for Testing and Materials 1984) size designation No. 57 and natural fine aggregate. The gradings of both aggregates are shown in Table 1. The mixture also contained approximately 611 lb/cu yd of Type I portland cement and had a water-cement ratio (W/C) of 0.33. Mixture proportions are given in Table 2.

6. Concrete was discharged from the truck mixers into a front-end loader bucket, transported to the prepared sand-clay base, and spread to the approximate desired grade. A 19,000-lb single steel-drum vibratory roller was used to compact the mixture. An approximate 3-in. layer of sand was spread on the compacted pavement surface and moistened periodically for 3 days in order to cure the RCC. Samples were taken from the pavement approximately 3 months after construction.

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 4.

Ft. Hood, TX

7. An 18,150-sq yd RCC parking area was constructed adjacent to a tactical equipment maintenance shop in July 1984. The 10-in.-thick pavement is designed to support 120,000-lb tracked vehicles as normal traffic.

8. All concrete materials were mixed in a continuous mixing pug mill. Two mixtures were used in the pavement; one having a 37.5-mm (1-1/2-in.) nominal maximum size aggregate (NMSA), and the second having a 19.0-mm (3/4-in.) NMSA. Natural fine aggregate was used in both mixtures. Aggregate gradings are shown in Table 1. The 37.5-mm (1-1/2-in.) NMSA mixture contained approximately 306 lb/cu yd Type I portland cement and 162 lb/cu yd Class C fly ash, and had a W/C of approximately 0.31. The 19.0-mm (3/4-in.) NMSA mixture contained approximately 376 lb/cu yd Type I portland cement and 186 lb/cu yd Class C fly ash, and had a W/C of approximately 0.30. The concrete mixture proportions for both are given in Table 2. Only the pavement containing the 37.5-mm (1-1/2-in.) NMSA mixture was sampled and tested in this investigation.

9. The no-slump concrete was placed on a 6-in.-thick lime-stabilized base with an asphalt paver, and compacted with 20,000-lb dual steel-drum vibratory roller. Damp cotton mats were used to moist cure the RCC for the first 24 hours, at which time the mats were removed and a pigmented membrane-forming curing compound was applied. The pavement test section was sampled approximately 1 month after its construction.

Ft. Lewis, WA

10. A 700-ft-long by 22-ft-wide RCC pavement test section, ranging in thickness from 6 to 7-3/4 in., was constructed in October 1984. The test

section currently serves as a secondary road for both rubber-tired and tracked vehicles.

11. Two concrete mixtures were used in the pavement. One contained 19.0-mm (3/4-in.) NMSA natural coarse aggregate conforming to the grading limits of ASTM C 33 (American Society for Testing and Materials 1984) size designation No. 67, and natural fine aggregate. This mixture also contained approximately 320 lb/cu yd Type I portland cement and 172 lb/cu yd Class F fly ash, and had a W/C of approximately 0.32. The second mixture contained both coarse and fine crushed aggregate graded from a 12.5-mm (1/2-in.) nominal maximum size to the 75-μm (No. 200) sieve size. This aggregate was typical of one which might be used in an asphalt paving mixture. The concrete also contained approximately 499 lb/cu yd Type I portland cement, and had an approximate W/C of 0.41. No fly ash was included in the second mixture. The aggregate gradings and concrete mixture proportions used for this project are given in Tables 1 and 2, respectively.

12. The concrete materials were mixed in a continuous mixing pug mill, and the resulting concrete was placed with an asphalt paver. Compaction was achieved using a single steel-drum vibratory roller having a mass of approximately 20,000 lb. A rubber-tired roller was also used to knead and tighten the RCC surface. Following the compaction operations, the concrete was continuously moist cured for 7 days by use of a water spray system. Hardened pavement samples representing each mixture were obtained approximately 3 weeks after completion of construction.

US Army Cold Regions Research and Engineering Laboratory (USACRREL)

13. These nominal 25- by 18-ft by 8-in. RCC pavement test sections were constructed in November 1984. One of the test sections contains concrete

having a 19.0-mm (3/4-in.) nominal maximum size natural aggregate. The aggregate was graded in a single size range to the 75-μm (No. 200) sieve size. Approximately 564 lb/cu yd of Type II portland cement were used in the mixture. The W/C was approximately 0.37.

14. A second section was constructed with no-slump concrete containing crushed coarse aggregate having a 19.0-mm (3/4-in.) nominal maximum size, and a natural fine aggregate. The concrete also contained approximately 567 lb/cu yd of Type II portland cement and had a W/C of approximately 0.35.

15. The third test section was constructed with a concrete mixture similar to that used in the second test section, except that an air-entraining admixture (AEA) consisting of an aqueous solution of neutralized Vinsol resin was added. The aggregate gradings and concrete mixture proportions used in the three RCC test sections are shown in Tables 1 and 2, respectively.

16. A pug mill of the batch type, normally used for asphalt production, was used to mix the concrete materials. The concrete was placed with an asphalt paver onto a crushed bank-run gravel base, and compacted with a dual steel-drum vibratory roller having a mass of approximately 20,000 lb. The completed test sections were moist cured 14 days using damp burlap strips. The pavements were sampled approximately 1 month after completion of construction.

Port of Tacoma, Intermodal Railyard Development, WA

17. This nominal 90,000-sq yd RCC pavement varies in thickness from 12 to 17 in. It was constructed in April 1985, and serves as a container storage facility.

18. The no-slump concrete mixture contained a crushed aggregate including both fine and coarse material having a nominal maximum size of 12.5 mm (1/2 in.) and graded to the 75-μm (No. 200) sieve size. The aggregate was

typical of that used in asphalt paving. The mixture also contained 450 lb/cu yd Type I portland cement and 100 lb/cu yd Class F fly ash, and had a W/C of approximately 0.43. The aggregate grading is given in Table 1 and the mixture proportions in Table 2.

19. The materials were mixed in a continuous mixing pug mill, and the resulting concrete was placed in two equal layers with asphalt pavers onto a crushed gravel base. Dual steel-drum rollers, each having a mass of approximately 20,000 lb, were used to compact the concrete and a rubber-tired roller was used to tighten the pavement surface. Water-spray trucks were used to moist cure the RCC for 7 days after completion of compaction. Samples were taken from the pavement approximately 3 weeks after construction was completed.

Caycuse, British Columbia

20. A RCC dry-land log sorting yard was constructed on Vancouver Island in 1976. The concrete covers an area of approximately 22,000 sq yd and has a nominal thickness of 14 in. A single-size range aggregate having a 19.0-mm (3/4-in.) nominal maximum size and graded to the 75-μm (No. 200) sieve size was used in the concrete. The aggregate grading and concrete mixture proportions were not available to the author at the time this paper was prepared. However, the contractor responsible for constructing the pavement has reported that approximately 8 percent of the aggregate, by mass, was finer than the 75-μm (No. 200) sieve, and that two mixtures were used in the pavement. A mixture containing approximately 7 percent portland cement, by mass of the aggregate, was used in the lower 8 in., and one containing approximately 12 percent portland cement, by mass of the aggregate, was used in the upper 6 in.

21. Concrete materials were mixed in a continuous-mixing pug mill. The concrete was placed with an asphalt paver and compacted with single steel-drum

vibratory rollers. Samples were taken from the pavement approximately 8 years after it was constructed.

Laboratory Fabricated Specimens

22. In addition to the RCC pavements previously described, specimens were also fabricated for test by WES and NPDL as part of the USACRREL and Ft. Lewis mixture proportioning studies. The concrete materials used by both laboratories were mixed in small revolving-drum mixers. Specimens for rapid freezing and thawing, compressive strength, and flexural strength tests were fabricated on vibrating tables with the aid of surcharge weights. The aggregate gradings and mixture proportions used in the laboratory studies are given in Tables 1 and 2, respectively.

PART III: TEST PROGRAM

23. As was previously stated, the primary purpose of the investigation discussed in this paper was to characterize the air-void system parameters and evaluate the frost resistance of samples obtained from RCC pavements. At least one representative sample from each pavement described herein was microscopically examined in accordance with ASTM C 457 (American Society for Testing and Materials 1984), Modified Point-Count Method, in order to determine the air-void content and bubble spacing factor ($\bar{L}$). Initially, the entrained and entrapped air-void content of each sample was determined. The criteria given in the definition of "air void" in ASTM C 125 (American Society for Testing and Materials 1984) were used to distinguish entrained and entrapped air voids. However, the predominant irregular shape of the observed sections of the small air voids, discussed in further detail below, resulted in very low entrained air-void contents in the samples. These results seemed inconsistent with what one might expect, given the relatively small $\bar{L}$'s determined in a number of the samples. Therefore, the decision was made to characterize the air voids by size only, irrespective of shape. Determinations were made for each specimen of the percentage of voids whose section chord lengths were less than 0.04 in. and the percentage of those whose section chord lengths were greater than 0.04 in.

24. The rapid freezing and thawing tests were conducted in accordance with applicable sections of ASTM C 666, Procedure A (American Society for Testing and Materials 1984). Samples were sawed into 3-1/2- by 4-1/2- by 16-in. prisms and stored in a 73° F water bath for 14 days prior to the start of testing. Each specimen was continued in test until it was subjected to 300

freezing and thawing cycles or until its relative dynamic modulus of elasticity reached 50 percent of the initial modulus, whichever occurred first. The NPDL conducted the freezing and thawing tests on the Ft. Lewis and Caycuse samples, as well as the NPDL fabricated specimens. The SWDL conducted the freezing-and-thawing tests on the Ft. Hood samples. WES conducted the testing on the remainder of the samples.

25. The dilation test (ASTM C 671 (American Society for Testing and Materials 1984)) was also used as a means to evaluate the potential frost resistance of the samples. The test may also be used to determine whether or not a specimen becomes frost susceptible during a particular period of interest. Powers stated that concrete frost resistance or durability is not a measurable property, but that the expansion which occurs during a slow cooling cycle when the concrete or its aggregates become critically saturated is measurable, and will provide an indication of potential frost resistance. That is, if a specimen shrinks normally in the freezing range, it is immune to frost action; if it dilates it is not immune (Powers, 1955). ASTM C 671 requires that dilation be determined by measuring the vertical distance from a straight-line projection of the prefreezing, length-versus-time contraction curve, at constant cooling rate, and the maximum deviation of the strain from it. The test is conducted by monitoring the length of a specimen as its temperature is lowered.

26. There were some differences in the dilation test method followed in this investigation and that prescribed by ASTM. The major one was that the 3-in.-diameter by 6-in.-long RCC cores were cooled in water-saturated kerosene from an unspecified but convenient temperature range of 35 to 55° F at a rate

of approximately 5° F per hour to a minimum of -10° F. The ASTM method specifies cooling the specimens in water-saturated kerosene from 35 to 15° F at 5° F per hour. Critical dilation (D_c) in ASTM C 671 (American Society for Testing and Materials 1984) is defined as the dilation during the last cycle before the dilation begins to increase sharply by a factor of 2 or more. The method states that dilations less than 0.005 percent should not be interpreted as indicating D_c even if the criterion for D_c is met numerically.

27. Dilation criterion, based on the results of a single test, has also been proposed by Buck (1976). He suggests the following:

a. If the dilation is 0.005 percent (= 50 millionths) or less, the specimen may be regarded as frost resistant, i.e., the dilation is not critical.

b. If the dilation is 0.020 percent (= 200 millionths) or more, the specimen may be regarded as not frost resistant, i.e., D_c has been exceeded.

c. If the dilation is in the range between 0.005 percent and 0.020 percent, an additional cycle or more should be run.

28. Ten specimens representing six of the nine pavements were tested. At the time this paper was prepared only five to seven freezing cycles per specimen were completed. Test results were evaluated using both the ASTM dilation criterion and that suggested by Buck.

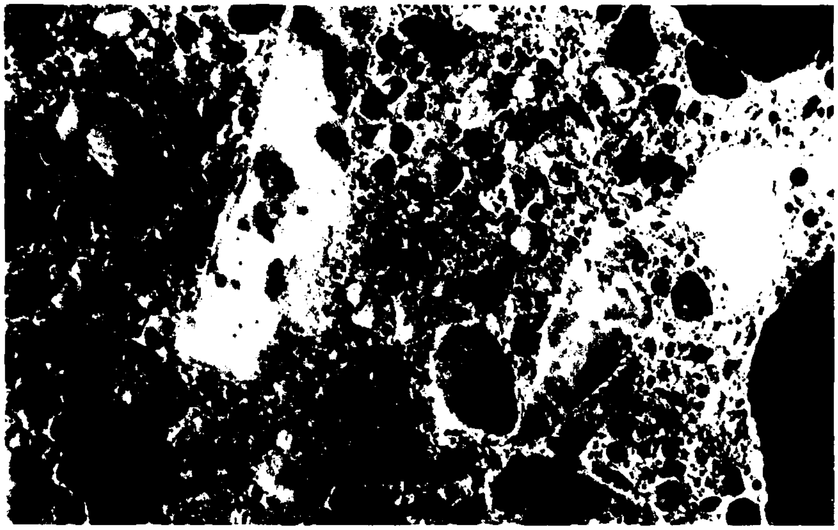
29. Compressive and flexural strength tests provided physical data on samples representing each pavement. The tests were conducted in accordance with ASTM C 42 (American Society for Testing and Materials 1984).

PART IV: TEST RESULTS AND DISCUSSION

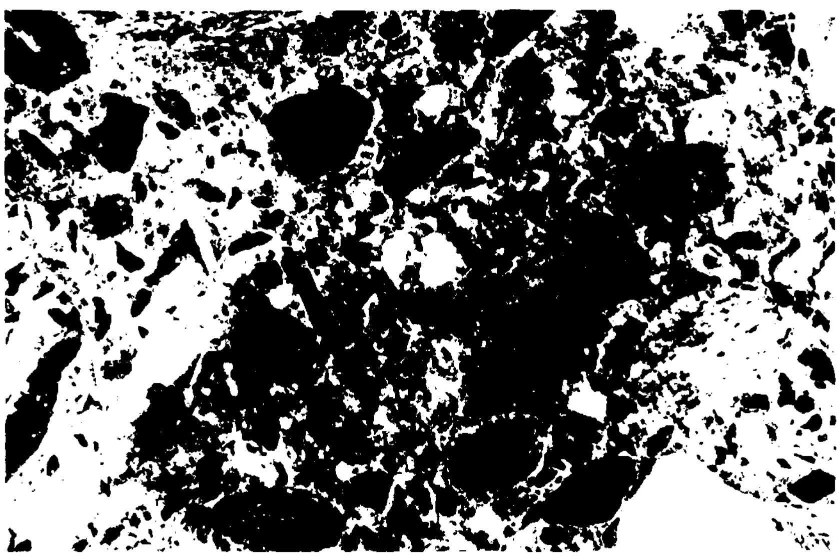
30. The air-void size distribution and $\bar{L}$ of each RCC sample is given in Table 3. As was previously noted, the air voids were categorized according to chord lengths of the counted air-void sections, irrespective of section shape. Figure 1 shows a typical RCC and conventional air-entrained concrete polished section. The irregular shape of the voids in the RCC section is believed to result from compaction operations associated with RCC pavement construction. However, no work was conducted in this investigation to confirm this belief.

31. The percentage of air voids, by volume, smaller than 0.04 in. ranged from 0.1 to 9.6 in the pavement samples, and from 0.6 to 2.5 in the laboratory fabricated specimens. Large dosages of AEA were added to the mortar fraction of the concrete represented by USACRREL, specimen No. C-2T, and WES specimen No. B-1. The mortar was mixed for approximately 1 minute prior to the addition of the coarse aggregate. The USACRREL concrete was mixed in a pug-mill mixer of the batch type, and the WES concrete was mixed in a small revolving-drum mixer. The effect of the AEA on the concrete air-void system is somewhat ambiguous. Specimen C-2T has 2.9 percent, by volume, of air voids smaller than 0.04 in. and 2.3 percent of the voids larger than 0.04 in. However, USACRREL specimen No. B-3B, which represents similar concrete without AEA, has 3.6 percent of the air voids smaller than 0.04 in. and 5.0 percent which were larger. Similarly, USACRREL specimen No. A-1B, which also represents a nonair-entrained concrete, has 2.3 percent of the air voids smaller than 0.04 in. and 3.2 percent larger than 0.04 in. The $\bar{L}$'s of the three specimens are not significantly different.

32. WES specimen No. B-1 had 2.5 percent, by volume, of its air voids smaller than 0.04 in. and 2.1 percent of the voids larger than 0.04 in. WES



Conventional air-entrained concrete



RCC

Figure 1. Polished sections showing air-void shapes, magnification = 5.5

specimen No. A-1, which represents similar concrete without AEA, had 1.1 percent of its voids smaller than 0.04 in. and 2.0 percent larger than 0.04 in. However, the $\bar{L}$ of specimen No. A-1 is approximately 2.5 times that of specimen No. B-1.

33. Those specimens representing concrete which was pug-mill mixed generally had greater percentages of air voids smaller than 0.04 in. than those specimens representing concrete which was mixed in revolving-drum mixers. The specimens representing pug-mill mixed concrete also generally had smaller $\bar{L}$'s. Although the mechanisms responsible for creating these desirable air-void systems in the nonair-entrained concrete are not yet fully understood, pug-mill mixing appears to be a contributing factor. The cohesiveness of the mixture may also play an important role in the maintenance of the small air voids during compaction. An RCC mixture which is highly cohesive due to a low water content and large aggregate surface area may prevent the escape of a large percentage of the small air voids during the compaction operations. Additional investigative work is needed to confirm these proposed explanations.

Rapid Freezing and Thawing Tests

34. Table 4 presents the summarized rapid freezing and thawing test results. In general, these values may be interpreted (Neville 1981) as follows: a DFE_{300} less than 40 means that the concrete is probably unsatisfactory with respect to frost resistance; 40 to 60 is the range for concretes with doubtful performance; and greater than 60, the concrete is probably satisfactory. Using these criteria, the test results indicated that the RCC samples associated with Ft. Stewart, Ft. Hood, and Caycuse were frost susceptible, as were the WES and NPDL fabricated specimens. The results of the tests

of the Ft. Lewis specimens indicate doubtful to satisfactory performance, while the USACRREL and Port of Tacoma test results indicate satisfactory performance.

35. The rapid freezing-and-thawing test results and specimen $\bar{L}$'s are paired in Table 5. This summarization indicates that the frost resistance of RCC is, as expected, a function of the $\bar{L}$. Spacing factors less than 0.008 in. are typically associated with concrete having good resistance to freezing and thawing. In the case of the tests of RCC it was found that $\bar{L}$'s smaller than 0.011 in. generally resulted in DFE_{300}'s of 60 or greater; $\bar{L}$'s of 0.011 to 0.016 in. resulted in $DFE_{300's}$ of 40 to 60; and $\bar{L}$'s greater than 0.016 resulted in DFE_{300}'s less than 40. The relatively small $\bar{L}$ coupled with the low DFE_{300} of the Ft. Hood specimen was unexpected. However, it is not known if the aggregates used in the RCC are frost susceptible. The small $\bar{L}$ and low DFE_{300} of Ft. Lewis specimen A-10B was unexpected and unexplainable. Figure 2 graphically shows the relationship between DFE_{300} and $\bar{L}$ of the RCC samples. The figure is subdivided into zones of performance based on the criteria noted above.

Dilation Tests

36. The rapid freezing-and-thawing test uses a higher freezing rate than is ordinarily encountered in outdoor weathering. Cooling takes place at approximately 25° F/hr in the laboratory test, while in practice 5° F/hr is not normally exceeded. The dilation test was selected as an alternate means of evaluating the frost resistance of some of the pavement samples since the cooling rate used in the test is comparable to natural cooling rates. Powers suggested when dilation testing specimens which represent concrete subject to

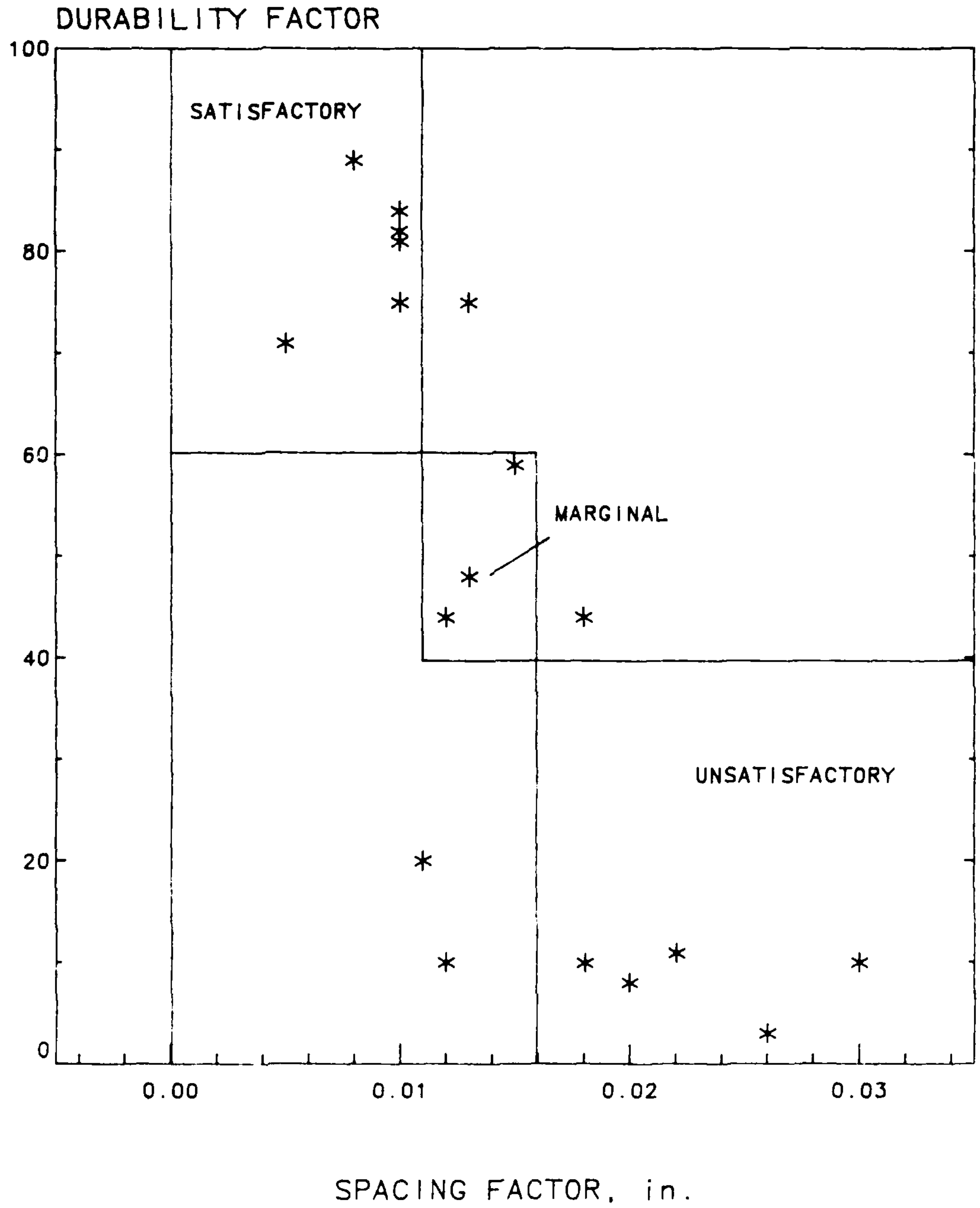


Figure 2. Durability factor (DFE_{300}) versus factor ($\bar{L}$), based on data from Table 5

seasonal drying, a period of immunity of approximately 16 weeks (8 freezing cycles) of continuous exposure to water should assure immunity during any winter season (Powers, 1955). Studies by Larson and Cady suggest that the length of the period of soaking exerts considerably more influence on the rate of deterioration than do the number of intermediate cooling cycles (Larson and Cady, 1969).

37. Table 6 shows the specimen dilation test results. It is apparent from this table that a variation of 100 to 200 μin. between cycles for a specimen is not indicative of damage. Each of the specimens appears to be immune to frost damage, as defined by ASTM C 671 (American Society for Testing and Materials, 1984), for the first five to seven cycles of test. However, USACRREL specimen No. A-4, Ft. Stewart specimen No. FS-4, and Ft. Hood specimen No. 20-F, each experienced large dilations after six, five, and three cycles, respectively, and additional testing may result in dilation in excess of D_c.

38. The single-test dilation criterion suggested by Buck (1976) indicates that, in general, all of the specimens fall in the marginal zone between frost resistant and frost susceptible. This is, the dilation value obtained during the last freezing cycle of each is generally within the range of 50 to 200 millionths. This suggests that additional cycles should be run to determine when the D_c of 200 millionths is exceeded. Regardless of the dilation criterion used to evaluate the results, it is apparent that each of the specimens tested has some resistance to frost damage down to -10°F for at least 5 to 7 cycles (10 to 14 weeks of continuous exposure to water). In the case of those samples having large $\bar{L}$'s, the low W/Cs were apparently adequate to provide a measure of protection.

Compressive and Flexural Strength Tests

39. A summary of the sample compressive and flexural strength test results is shown in Table 7. The average compressive strengths range from 2930 to 8920 psi, and the average flexural strengths range from 510 to 1010 psi.

PART V: CONCLUSIONS

40. The microscopical examinations of representative sections of the RCC pavement samples indicate that air-void systems normally associated with at least partially frost-resistant concrete may be created without the use of AEA. The creation of these air-void systems appears to be related to pug-mill mixing, the cohesiveness of the mixture, and the method of compaction. The inclusion of AEA in the mortar fraction of a no-slump concrete mixture which was pug-mill mixed did not significantly increase the percentage of air voids smaller than 0.04 in.

41. The shapes of the examined air-void sections were irregular. These irregular shapes are believed to result from the compaction operations associated with RCC pavement construction.

42. The frost resistance of RCC, as evaluated by the DFE_{300}, is a function of $\bar{L}$. Durability factors of 60 or more were associated with those specimens having $\bar{L}$'s smaller than 0.011 in. Those specimens having $\bar{L}$'s of 0.011 to 0.016 in. resulted in DFE_{300}'s of 40 to 60, and those having $\bar{L}$'s larger than 0.016 in. resulted in DFE_{300}'s less than 40.

43. The dilation test appears to provide an effective measure of the frost resistance of RCC. Use of the test would seem appropriate to determine whether a sample of RCC is frost resistant at the time of test or to measure the period of frost immunity. The latter use might be particularly important in the case of pavements, which are typically subject to seasonal drying.

44. The dilation data indicate some degree of frost resistance for each specimen tested. The frost resistance of specimens having large $\bar{L}$'s may be attributed to the low W/C of the RCC mixtures. Such concrete has little

freezable water in the paste, and also has a low permeability. Therefore, it is more difficult to critically saturate.

45. Concrete must meet three requirements before it may be considered immune to frost action. It must be made with nonfrost-susceptible aggregates and a proper air-void system, and must be cured to an appropriate degree of maturity so as to reduce the fractional volume of freezable water on saturation to limits that can be accommodated by elastic volume change and by the air-void system. RCC pavements can be constructed with nonfrost-susceptible aggregates, and can be appropriately cured. The air-void systems observed in many of the sampled RCC pavements should be sufficient to protect them against frost damage in all but the most severe environments. Additional investigative work is needed to determine if an entrained air-void system can be effectively produced in RCC which would cause it to be immune to frost damage in all exposures.

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Table 1

RCC Aggregate Gradings

	Cumulative Percent Passing						
	Ft. Stewart, GA		Ft. Hood, TX			Ft. Lewis, WA (Natural Concrete Graded)	
50 mm (2 in.) [(a)]			100				
37.5 mm (1-1/2 in.)	100		98				
25.0 mm (1 in.)	95		30	100		100	
19.0 mm (3/4 in.)	71		8	97		83	
12.5 mm (12/ in.)	31		--	---(b)		47	
9.5 mm (3/8 in.)	11		1	42		25	
4.75 mm (No. 4)	2	99		8	100	1	100
2.36 mm (No. 8)		96		0	90	1	84
1.18 mm (No. 16)		86			69		64
600 μm (No. 30)		57			45		40
300 μm (No. 50)		20			17		15
150 μm (No. 100)		4			4		4
75 μm (No. 200)		1			1		2

Table 1 (Continued)

Sieve Size	Cumulative Percent Passing			
	Ft. Lewis, WA (Crushed Asphalt Graded)	USACRREL (Pit-Run)	USACRREL (Concrete Graded)	
50 mm (2 in.)				
37.5 mm (1-1/2 in.)				
25.0 mm (1 in.)		100	100	
19.0 mm (3/4 in.)	100	99	99	
12.5 mm (1/2 in.)	98	--	68	
9.5 mm (3/8 in.)	86	77	31	100
4.75 mm (No. 4)	60	69	2	99
2.36 mm (No. 8)	41	55	1	87
1.18 mm (No. 16)	29	43		68
600 μm (No. 30)	19	33		43
300 μm (No. 50)	11	24		15
150 μm (No. 100)	6	14		4
75 μm (No. 200)	--	8		2

Table 1 (Concluded)

Sieve Size (a)	Cumulative Percent Passing				
	Port of Tacoma	WES Beams		NPDL Beams	
50 mm (2 in.)					
27.5 mm (1-1/2 in.)					
25.0 mm (1 in.)		100		100	
19.0 mm (3.4 in.)	100	93		95	
12.5 mm (1/2 in.)	98	--		54	
9.5 mm (3/8 in.)	85	25		29	100
4.75 mm (No. 4)	55	4	99	2	97
2.36 mm (No. 8)	41	1	87	1	74
1.18 mm (No. 16)	31		71		56
600 μm (No. 30)	22		42		35
300 μm (No. 50)	15		13		15
105 μm (No. 100)	10		7		3
75 μm (No. 200)	5		--		--

(a) U.S. standard sieves
(b) Dash indicates data not available

Table 2

Mixture Proportions

Weight, Saturated Surface-Dry, lb/cu yd

Project	Portland Cement	Fly Ash	No. 4–3/4 in.	No. 4–1 in.	No. 4–1-1/2 in.	No. 4–No. 200	3/4 in.–No. 200	Water	AEA oz
Ft. Stewart, GA	611	--(a)	--	1971	--	1406	--	202	--
Ft. Hood, TX (A)	306	162	--	--	2294	1285	--	153	--
(B)	376	186	2165	--	--	1366	--	180	--
Ft. Lewis, WA (A)	320	172	1967	--	--	1546	--	176	--
(B)	499	--	--	--	--	--	3468	206	--
USACRREL (A)	564	--	--	--	--	--	3336	209	--
(B)	567	--	1745	--	--	1640	--	199	--
(C)	567		1745			1640		199	40
Port of Tacoma	450	100	--	--	--	--	3400	256	--
WES Beams (A)	561	--	1960	--	--	1472	--	196	--
(B)	548	--	1837	--	--	1437	--	191	41
NPDL Beams	351	180	1936	--	--	1560	--	169	--

(a) Dash indicates material not used.

Table 3

Microscopical Air-Void Data

Project	Mixture	Air Content With Chord Lengths				
		Specimen No.	Smaller Than 0.04 in., Percent	Larger Than 0.04 in., Percent	Total Air Content Percent	$\bar{L}$, in.
Ft. Stewart, GA		1T1	0.2	8.0	8.2	--
		1B1	0.1	3.7	3.8	--
		2T1	1.9	3.4	5.3	0.020
		2B1	0.8	21.6	22.4	--
		3T1	0.6	2.5	3.1	--
		3B1	0.3	4.0	4.3	--
		4T1	0.8	10.0	10.8	--
		4B1	0.2	8.5	8.7	--
Ft. Hood, TX	A	1	1.3	1.6	2.9	0.012
Ft. Lewis, WA	A	5A	2.5	2.6	5.1	0.012
		9B	1.9	0.2	2.1	0.005
		10B	9.6	0.8	10.4	0.011
	B	17A	1.6	3.1	4.7	0.015
		17B	1.8	2.2	4.0	0.018

(Continued)

Table 3 (Concluded)

Project	Mixture	Specimen No.	Air Content With Chord Lengths: Smaller Than 0.04 in., Percent	Air Content With Chord Lengths: Larger Than 0.04 in., Percent	Total Air Content Percent	$\bar{L}$, in.
USACRREL	A	1T	--(a)	--	5.1	--
		1B	2.3	3.2	6.1	0.008
	B	3T	--	--	5.3	--
		3B	3.6	5.0	8.6	0.010
	C	2T	2.9	2.3	5.2	0.010
		2B	--	--	4.8	--
Port of Tacoma		2A-T	5.5	1.6	7.1	0.010
		2A-B	2.5	0.7	3.2	
		1D-T	3.0	1.5	4.5	0.013
		1D-B	4.1	0.5	4.6	--
		2H-T	3.5	2.0	5.5	--
		2H-B	6.1	4.5	10.6	0.010
Caycuse, B.C.		2A	0.5	10.8	11.3	0.026
WES Beams	A	1	1.1	2.0	3.1	0.030
	B	1	2.5	2.1	4.6	0.013
NPDL Beams		2	0.6	1.1	1.7	0.018
		8	0.9	0.8	1.7	0.019
		9	1.1	2.8	3.9	0.022

(a) Dash indicates data not determined.

Table 4

Summary of Results of Rapid Freezing and Thawing Tests

Project	Mixture	Specimen Nos.	Avg. DFE_{300}
Ft. Stewart, GA		1T1-1T6	8
		1B1-1B5	6
		2T1-2T2	9
		2B1-2B3	5
		3T1-3T4	8
		3B1-3B4	4
		4T1-4T4	6
		4B1-4B4	6
Ft. Hood, TX	A	5-7	10
		8-10	8
Ft. Lewis, WA	A	5A,B; 9A,B;10A,B	47
	B	17A-17D	59
USACRREL	A	1T-3T	88
		1B-3B	89
	B	1T-3T	39
		1B-3B	69
	C	1T-3T	68
		1B-3B	91
Port of Tacoma		1A-T,B;2A-T,B	82
		1D-T,B;2D-T,B	79
		1H-T,B;2H-T,B; 3H-T,B;4H-T,B	78
Caycuse, B.C.	12% Cement	1A-1C	6
		2A-2C	3

(Continued)

Table 4 (Concluded)

Project	Mixture	Specimen Nos.	Avg. DFE_{300}
WES Beams	A	1-3	10
	B	1-3	48
NPDL Beams		1-4	10
		5-9	11

Table 5

Summary of Specimen DFE_{300} and $\bar{L}$'s

Project	Mixture	Specimen Nos.	DFE_{300}	$\bar{L}$, in.
Ft. Stewart, GA		2T1	8	0.020
Ft. Hood, TX		5	10	0.012
Ft. Lewis, WA	A	5A	44	0.012
		9B	71	0.005
		10B	20	0.011
	B	17A	59	0.015
		17B	44	0.018
USACRREL	A	1B	89	0.008
	B	3B	75	0.010
	C	2T	81	0.010
Port of Tacoma		2A-T	84	0.010
		1DT	75	0.013
		2HB	82	0.010
Caycuse, B.C.		2A	3	0.026
WES Beams	A	1	10	0.030
	B	1	48	0.013
NPDL Beams		2	10	0.018
		8		0.019
		9	11	0.022

Table 6

Dilation Test Results

Project	Mixture	Specimen No.	Test Cycle 1	2	3	4	5	6	7
Ft. Stewart, GA		FS-4	375[a] 75[b]	425(85)	130(26)	250(50)	220(50)	430(86)	325(65)
Ft. Hood, TX	A	20-F	200(40)	230(46)	230(46)	450(90)	500(100)	575(115)	575(115)
USACRREL	A	4	200(40)	340(68)	300(60)	400(80)	300(60)	300(60)	550(110)
	B	4	175(35)	125(25)	125(25)	250(50)	175(35)	250(50)	175(35)
	C	4	250(50)	330(66)	330(60)	450(90)	450(90)	---(c)	550(110)
Port of Tacoma		3A-T	110(22)	--	190(38)	160(32)	210(42)	---	---
		3D-T	130(26)	175(35)	252(55)	250(50)	225(45)	---	---
		3D-B	130(26)	100(20)	210(42)	200(40)	330(66)	---	---
		5H-T	140(28)	275(55)	200(40)	330(60)	260(52)	---	---
		5H-B	100(20)	100(20)	275(55)	200(40)	290(58)		

(a) Microinches.
(b) Millionths.
(c) Dash indicates Malifunction.

Table 7

Summary of Compressive and Flexural Strength Test Results

Project	Mixture	Approximate Age, days	Average Compressive Strength, psi	Average Flexural Strength, psi
Stewart, GA		90	5220	1010
Ft. Hood, TX	A	28	4780	830
Ft. Lewis, WA	A	90	5790	690
	B	90	8920	960
USACRREL	A	40	2930	510
	B	40	6500	860
	C	40	4370	600
	C	40	6500	860
Port of Tacoma		35	5220	705
Caycuse, B.C.		8 years	5880	540
WES Beams	A	28	6250	730
	B	28	5740	680
NPDL Beams		28	6900	650

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